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SPARVIS: Combining Smartphone and Augmented Reality for Visual Data Analytics

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Figure 1: A user explores the Chicago crime dataset with SPARVIS, a cross-device system that combines a smartphone as an adaptive controller and AR glasses as a display. In the system, the user opens up three windows to compare crimes in different regions of Chicago at the same time. The user holds his smartphone horizontally so it is on trackpad mode and he can interact with visual elements within the selected window.

Abstract

We present SPARVIS, a conceptual framework that combines the strength of both AR and smartphones to enhance visual data analytics. The framework uses AR to display coordinated visualizations and a smartphone to interact with and organize them. This design enables users to take advantage of their surrounding space to externalize and organize their intermediate analysis results in an AR environment and manipulate the visualizations via familiar smartphone interactions. We identify four interactions that are fundamental to visual analytics tasks and propose alternative implementations of these techniques in the SPARVIS framework following existing design guidelines. We run an empirical evaluation to quantitatively test the efficiency and physical demand of two alternative implementations of the "click" mechanism (the most fundamental one among the four) and provide design suggestions based on the study result. We further develop a prototype application based on the framework to illustrate SPARVIS's usage and conduct a user study with 22 participants to validate its usability. Based on the finding, we provide implications for research and design of integrating AR and smartphone for visual data analytics.

Keywords: Immersive Analytics, Visual Data Analytics, Augmented Reality

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

Traditional desktop-based visual data analytics (VDA) struggles at dealing with cognitive loads raised as a result of limited display real estate, which prevents analysts from efficiently externalizing their thoughts and retrieving them [47]. As a result, analysts spend much of their working memory keeping intermediate results instead of conducting analytic and computational tasks [26]. The large display allows analysts to organize and coordinate views with a higher degree of freedom and hence reduce cognitive costs [19], but they are not affordable for ordinary users and not mobile enough. Technological advancement of wearable, mobile, and head-mounted devices (HMDs) has raised enormous opportunities for data visualization and analysis to go beyond desktop [39]. Mobile devices

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have become the *de facto* personal computer in people's daily life and they have demonstrated potential to play a big role in professional VDA [22]. Additionally, the ever-evolving augmented reality (AR) has reached maturity to support knowledge work seamlessly. Time has come for us to make full use of AR for its unlimited space around the user [3, 14, 25, 42], 3D interactions [30, 43], and spatial memory [35].

To take advantage of AR's strength while mitigating its drawback (e.g., physically tiring interactions), some research has proposed combining AR glasses with mobile devices while the latter enriches the interaction vocabulary of the system and minimizes physical fatigue raised when executing interactions [45]. Applications proposed following this line of research are deemed as AR-centric [48], where the user mostly looks at windows presented in the AR space and a smart device serves as an interface through which the user interacts with things in the AR world. One challenge in designing an AR + smartphone-based VDA experience is to figure out what roles the smartphone should play. Previous research has indicated it should be used as a smart controller [41].

In this paper, we explore the fundamentals and investigate the usefulness of using AR as a display supplier and mobile smartphone (tablet) as an adaptive controller and primary input interface for data visualization. The combination of these technologies not only mitigates the weakness of each module but also opens up a new design space – the usage of physical space around the user to display information through AR glasses – beyond the affordance of a traditional desktop setup.

Specifically, the main contributions of this paper include:

1. We propose a conceptual framework for a set of four common and atomic visualization interactions (click, drag, pan, zoom) that are important within an AR + smartphone space. For each interaction, we propose two smartphone-based interaction modalities, one where the smartphone acts as a raycaster, and one where it acts as a trackpad.

2. To help demonstrate this conceptual framework, we implement a prototype AR + smartphone VDA application and conduct a user study to test the effectiveness of the click interaction based on using the smartphone as a raycaster and as a trackpad. Based on the study results, we analyze and discuss how different smartphone control modes (raycaster vs. trackpad) can provide advantages and disadvantages in the user experience, and how future work can further explore interactive visual analysis within an AR + smartphone space.

2 Related Work

2.1 Immersive Analytics

Immersive analytics (IA) – the use of immersive technology to facilitate data analysis – has now fully emerged as a research topic that spans various communities including HCI, DataVis, AR, and VR [12]. Prior work has identified and evaluated benefits of incorporating immersive technology for data analysis such as: unlimited space around the user [3, 14, 25, 42], 3D interactions [30, 43], and spatial memory [35].

Data can be presented in both 2D and 3D formats with immersive technology. Although straightforward, representing data in 3D in an immersive space does not always bring benefits and the use of 3D requires careful inspection and contemplation [1]. On the other hand, 2D representation leads to less clutters [9], higher accuracy in selection task [10], and is more suitable for presenting abstract information [13]. Along this line of research, Lisle et al. [24] proposed a VR-based system that supports text-based document analytics by leveraging spatial organization and annotation of documents during the sensemaking process. Liu et al. [25] explored various ways to adapt 2D small multiple data visualizations in 3D immersive space. Satriadi et al. [42] investigated laying out 2D maps in 3D immersive space to take advantage of the virtually unlimited display real estate and spatial interaction for geographical data analysis. These works all focused on one specific type of data, i.e., text or map. To enable visual data analysis for general types of data, we need to consider scenarios where multiple dashboards are present, and moved around, and there is a UI that facilitates interactions with contents and manipulations of the dashboards. Research on 2D interfaces in immersive space provides guidelines that we can follow. Prior research has proposed feasible designs for 2D interfaces in 3D immersive space [13] and window switch mechanisms for 2D interfaces in 3D space [6, 15]. Our work draws inspiration from existing research for system design. However, prior work mainly focuses on applications in either AR or VR while overlooking the possibility of a cross-device design space where both AR and mobile devices are accessible. To the best of our knowledge, SPARVIS is the first system that combines AR glasses as a display supplier with a smartphone as an interaction provider to facilitate visual data analytics.

2.2 AR + Mobile Devices for Visual Data Analytics

The integration of multiple modalities has demonstrated various benefits for everyday knowledge work [11, 23, 31, 32]. Recently, the smartphone has become a popular interaction provider of AR glasses [27, 28]. HMD AR + mobile devices have the remarkable potential to facilitate and enhance VDA experience [20, 22, 45]. The design of cross-device experience on HMD AR + mobile either uses HMD AR to enhance mobile tasks (mobile-centric) or uses mobiles to enhance HMD AR tasks (AR-centric) [48].

Following the mobile-centric design strategy, Hubenschimid et al. [20] proposed an approach to combine multiple mobile and AR devices to make use of the location-awareness of mobile devices to afford tangibility and proxemics and support various spatially coordinated visualizations. Reichherzer et al. [36] proposed a framework for rapid interface development and evaluation on smartphone + AR platform. Langner et al. [22] proposed a conceptual framework that uses AR glasses to display additional 2D and 3D information around and above mobile displays and their limited screen space. When evaluating MultiFi [17], a framework that uses HMD AR to enhance tasks on mobile and wearable devices, Grubert et al. have found that the combination of smartwatch and HMD can outperform interaction solely on wearables.

Our work follows the AR-centric design, which aims to take full advantage of the unlimited display space, spatial memory, and spatial awareness that AR affords while employing mobile devices to compensate for the weakness of AR. For example, smartphone-based interactions in 3D data navigation can outperform AR's native mid-air gesture interaction in efficiency [8]. In this line of research, Sereno et al. [44] developed a system that supports collaborative volumetric data analysis by displaying data in AR and providing interactions via handheld tablets. Ren et al. [37] explored window management behaviors in an AR-centric interface and provides design suggestions. The closest work to ours is [45] where AR displays dashboards for data analytics and smartphone is used for interactions and display of additional information. However, their system does not make an explicit effort to take advantage of the "space to think" surrounding the user (i.e., letting users freely arrange and organize views around them). Using smartphones to display additional information also results in increased cognitive load since the user needs to switch focus between the AR display and smartphone screen. Our proposed framework avoids undesirable context switches by assigning orthogonal roles for AR and smartphones and we provide an interaction vocabulary suitable for the "AR as display and smartphone as adaptive controller" design.

2.3 Space Influences Visual Data Analytics

VDA is a sensemaking process and the space around the analyst influences the performance of analytics [2]. Earlier work has demonstrated how human users make use of spaces to reduce the memory load of tasks or the amount of internal computation necessary [21]. The spatial environment supports sensemaking by becoming part of the distributed cognitive process, providing both external memory and a semantic layer [2]. In VDA, the scale of spatial organization differs from tasks and visual abstractions [16].

Increased display real estate is beneficial to knowledge work – "The more times you have to flip, and flip from one screen to the next or open and close sessions, you lose your train of thought" [18]. On different display sizes, analysis tasks also influence the application of visualization techniques differently [40]. A larger display brings benefits such as enhanced spatial memory of locations where information is present [33], awareness of peripheral applications, and a more "immersive" experience [5]. These benefits preserve when the display goes from physical monitors to virtual display in AR glasses [26].

Although the limited field of view of current AR glasses design may impose cognitive load on graph viewing tasks, the usage of augmented space effectively reduces the load for memorizing intermediate results, leading to increased overall performance [4]. Andrews et al. [2] demonstrated how the spatial environment supports sensemaking by becoming part of the distributed cognitive process, providing both external memory and a semantic layer. SPARVIS aims to make use of the augmented space provided by AR devices to reduce the cognitive load of VDA process while decreasing the physical demand for using AR with a smartphone.

3 SPARVIS: Design and Framework

Based on reviewing prior work on AR + mobile systems and immersive analytics (see Section 2), we identify a set of design rationales (R1–3) that are central to our framework. Regarding the implementation of this framework, we focus on four atomic interactions (I1-4), that compose fundamental manipulation tasks for visual data analytics based on two established visualization task typologies [7, 46]. We propose two reasonable alternative designs for each of the interactions.

3.1 Design Rationales

1. Mimicking Desktop Experience The framework needs to stimulate familiarity to avoid overwhelming the users from the beginning. As most users perform everyday VDA tasks on a desktop setup, the interaction flow needs to provide similar usage and experience. To this end, we assign suitable roles for AR glasses and smartphones so that the combination of both can resemble daily desktop workflow. We designate the smartphone to be an adaptive controller that supports different functions under different contexts. For example, when the user interacts with a UI element in an AR display or needs more precise control of visual elements, the phone becomes a touchscreen trackpad that the user can use to control a virtual cursor on the AR interface as if they are using a desktop system. Moreover, the interface in AR needs to be familiar to the user as well, for which we use conventional WIMP (window, icon, menu, pointer) design.

2. Minimizing Display Switch between Devices Display switch is common in cross-device experiences. It refers to the action where the user switches their focus from one device to another. Switching focus between devices can increase cognitive load and make it cumbersome for the user to conduct analysis [29, 34]. For example, in an AR + smartphone cross-device experience, when the user switches from looking at virtual windows in AR to looking at the smartphone screen, they might lose track of what they saw in the AR display and have to go back and forth to make sure they are right with what they thought they have seen. To reduce or even prevent context switches in our framework, we aim to increase the presence of the user in the AR scene while minimizing or zeroing the need of seeing the smartphone. Our strategy is to minimize overlap between device functions so that AR glasses are used only for interface and visualization display while the smartphone is only used for interactions and manipulations.

3. Making Use of Surrounding Space The framework aims to overcome the limitation of desktop VDA experience, caused by insufficient display real estate. The framework should also facilitate users to externalize their thoughts and therefore release working memory for analytics tasks. This rationale is aligned with common visual data analytics workflow, where the most frequent tasks the users conduct are comparisons of different subsets with the same visual encoding or comparisons of different visual encoding of the same subset. Both tasks rely on multiple coordinated views in display [38]. Therefore, the framework also needs to provide support for easy manipulation of multiple windows and enable the user to arrange views freely.

3.2 Atomic Interactions

From studies on visual analytics theory, we extract four manipulations fundamentals to VDA experience – Selection, Navigation, Filtering and Arranging, [7] – which consist of four atomic interactions – Click, Drag, Pan, and, Zoom. On the cross-device duo of AR + smartphone, each atomic interaction associates with multiple possible implementations. Empirical studies are needed to determine which implementation is the best for which interaction. To this end, we ran a usability test which implementation is suitable for "click" interaction in the SPARVIS framework (Task 1 in Sec. 5). Testing for other interactions can be completed in like manner and we skipped those due to the dearth of time. We further summarize these interactions in the table of Fig. 2.

3.2.1 Click (I1)

"Click" is an action that bases many manipulations such as selection (click on an item) and filtering (click on UI elements with filtering function). To implement a "click" action on AR + smartphone setup, however, we have multiple alternatives differing from the role of the smartphone. When the smartphone acts as a raycaster, a "click" on a target object can be done by the user pointing the ray at the object and tapping the touchscreen to signify the action. Alternatively, when the smartphone serves as a trackpad, a "click" is viable by the user moving a cursor in a 2D virtual window where the target object is located and tapping the touchscreen when the cursor and the target object collide. Both implementations have their strength and weakness. While the raycasting mechanism allows the user to move fast from one location to another and can handle depth, it struggles at precise selection [45]. On the other hand, although cursor-based mechanism does not handle depth (the cursor only moves in a designated plane) and needs careful design to support rapid movement, it excels in precise selection. A usability test is needed to find out which implementation is more suitable for our framework.

3.2.2 Drag (I2)

"Drag" refers to the action where the user keeps holding an object in the UI and moves it with the pointer. It is frequently used in visual data analytics, sometimes with other actions. For example, during navigation, if users want to change viewpoint, they drag a spot and release it when they reach the viewpoint they wanted. Moreover, if users want to group select multiple data elements by brushing or lassoing, they rely on the drag to draw the selection area (lassoing). Similar to "Click", a "Drag" has two alternative implementations too. If the smartphone acts as a raycaster, the user points the ray at a location and tap and hold the touchscreen to initiate a drag. The drag action completes when the user releases. If the smartphone acts as a trackpad, a drag is implemented as it is in a desktop setup. As existing research has shown, raycaster-based interaction better accounts for large and long-distance movement while trackpad interaction provides higher precision for short-distance movement. We aim to empirically test the usability of both implementations in future work.

3.2.3 Zoom (I3)

Zooming is an important action for data navigation, a fundamental visual data analytics task. The user can zoom out to have an overview of the dataset and zoom in to look at details. Due to the different controller modes of the smartphone in SPARVIS, we have two alternative implementations for "Zoom". When the smartphone is a raycaster, the user can cast the ray at a location and swipe up and down the touchscreen to indicate the zoom direction. When the smartphone is a trackpad, users pinch/spread their fingers on the touchscreen to zoom out/in. These implementations may differ in physical demand and precision.

3.2.4 Pan (I4)

Similar to "Zoom", panning is essential to data navigation as well. The user pans to traverse various parts of a dataset at the same granularity level. Two alternative implementations of panning in the SPARVIS framework are: 1) when the smartphone is a raycaster, the user can cast the ray at a location, tap and hold the touchscreen to move the phone to indicate the pan direction; 2) when the smartphone is in trackpad mode, the user can perform a two finger drag on the smartphone screen. Similar to zoom, these implementations may differ in physical demand and precision.

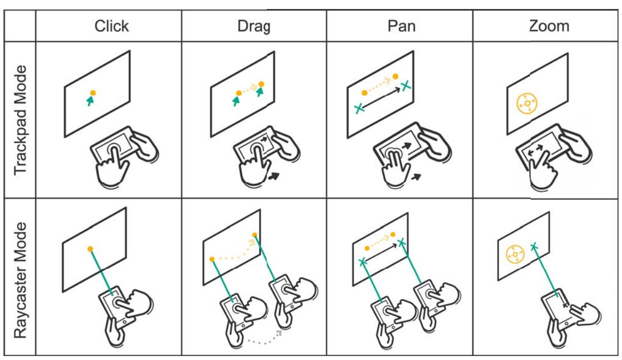

Figure 2: Each atomic interaction has two alternative implementations in both trackpad mode and raycaster mode

4 Dataset and Prototype Implementation

To demonstrate the use of our framework, we build an application based on SPARVIS framework and evaluate its overall usability with a user study (See Sec. 5). We use a real-world Chicago crime dataset [1] in the application. To avoid heavy data handling irrelevant to our purpose, we cleaned up the data and kept only crimes that happened in Feb 2018. The processed data set consists of approximately 2K individual crimes (data items) with 16 dimensions, such as date, time, location, primary crime type, community, longitude, and latitude.

4.1 The Interface

The visual interface (see Fig. 3) is designed so that it is usable for analyzing the dataset while having a decent coverage of both basic visualization types (e.g., pie chart, bar chart, and scatter plots) as well as complex visualizations (e.g., geographical maps). The top-left pie chart shows how crimes distribute across four time periods – early morning, morning, afternoon, and night. The actual percentage of a sector shows up when the user moves the virtual cursor to hover on it. The top-right bar chart shows how crime is distributed across 24 hours. Click a bar will select all crimes of the corresponding hour and hide other crimes. The mid-left line chart shows the trend of crime in Feb 2018 in Chicago. Clicking a dot in the line will select all crimes of the corresponding date and filter out other crimes as shown in the right window in Fig. 3. The mid-right geographical map is a community map of Chicago. Each community is colored by a distinct color. The user clicks a region to select a community for investigation. When a region is selected, the bottom-right map updates to show crimes in the selected region. The bottom-left chart shows the distribution of "arrest" (binary – a crime results in either an arrest or not) and "primary type" (categorical) attribute of all crimes.

[1] https://www.kaggle.com/datasets/chicago/chicago-crime

4.2 Interactions

The prototype application implements the SPARVIS framework (Fig. 3). The user uses the smartphone as a trackpad when interacting with visual elements within a window. When it comes to window management such as creating a new window or rearranging the positions of windows, the user uses the smartphone as a raycaster. The application emphasizes using AR to take advantage of the space around the user for more efficient data analysis through contrast and comparison.

In essence, the user is free to open as many windows as possible, an analog of having multiple screens around the user, so they can compare multiple aspects of the same dataset at one time. The window can also serve as the user's externalization of their thoughts. To open a new window, the user clicks the ">>" button on the top right corner of an existing window and a new one with the same visual configuration as the old one will be generated. The user can interact with the new window so that it reflects different aspects compared with the old one where it came from. To switch between windows the user tilts the phone to go from trackpad mode to raycaster mode and "click" the ○ button of the intended window with the ray hitting it to confirm a windows switch (See discussion for more elaborated results regarding the design of this mechanism). In terms of window management, the user can hit × button to close a generated window. To rearrange the windows in the space, the user can switch to raycaster mode and hit the ⤢ button. The user then can drag a window and move it around to position it at a suitable place for the analysis.

5 User Study

We run an empirical evaluation to quantitatively test the efficiency and physical demand of two alternative implementations of the "Click" mechanism (See Sec. 3.2.1). For demonstration purposes, we evaluate the overall usability of our prototype application with two data exploration tasks. Our observation of user behavior in the prototype system confirms the essentiality of "click" interaction.

5.1 Participants and Apparatus

We recruited twenty two participants from a local university (average age = 25.04, SD = 4.29; 16 males, 5 females, 1 other). Prior to the study participants self-reported their familiarity with AR on Likert scale with 1 being completely inexperienced and 7 being very familiar. The average familiarity is 3.7 with SD of 1.7. The experiment was conducted on a company's proprietary android smartphone and AR glasses. The experimental application was developed with Unity3D.

5.2 Procedure

Participants took the following procedure for the study:

(1) Training Stage. Participants first completed a short questionnaire regarding demography and AR experience. Next, they were

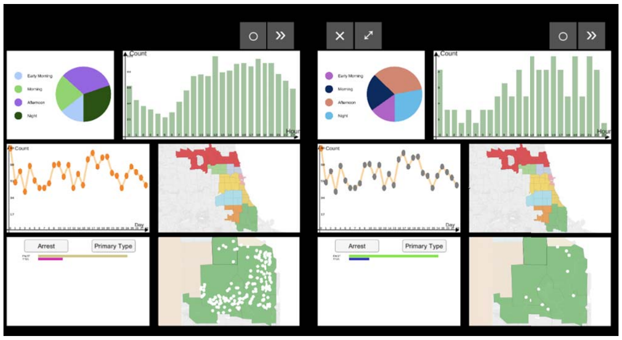

Figure 3: Our prototype application that implements SPARVIS framework. The user starts the analysis with the window on the left. As the user proceeds to a more detailed analysis on a specific date – Feb 1st, the user creates a new window by hitting the “>>” button on the top right corner. After the new window is created, the user switches to raycaster mode and clicks the ○ button of the new window to confirm interactions with it. The user then switches to trackpad mode and selects the circle representing Feb 1st in the line chart to further the analysis.

given a brief (high-level) introduction of the tasks and available interactions. Participants opted whether or not to complete a simple training task to help familiarize themselves with the system before getting into the task. During the training, participants could ask questions at any time and were allowed to play around with the interface until they felt comfortable to proceed.

(2) Task Stage. Participants completed the following three tasks (T1-T3). T1 is a usability test for two alternative implementations of the “Click mechanism”, while T2 and T3 aim at testing the usability of the prototype application.

T1: In this task, the user uses either a cursor-based mechanism or a raycaster-based mechanism (Fig. 3) to select 10 golden balls randomly distributed within a 5 x 10 grid of balls in the AR display. The task consists of ten rounds of raycaster selection tests and ten rounds of cursor selection tests. The time the user takes to complete a round is recorded.

T2: In this task, the user uses the prototype application to investigate the temporal pattern of primary crime type distribution for crimes in Chicago (Fig. 2).

T3: In this task, the user uses the application to investigate the spatial-temporal pattern of primary crime type distribution for crimes in Chicago.

The task order was consistent. Participants were encouraged to think aloud during tasks; the administrator listened to verbal utterances to help confirm that the participant was correctly performing the task. Upon completion of a task, the participant answered questions in a post-task questionnaire.

(3) Review Stage. Participants completed a short usability survey to rate different aspects of user experience and gave feedback; they were also allowed to provide comments or critiques about the prototype application.

5.3 Study Results

We report on qualitative verbal comments and responses given by participants, which were collected via the think-aloud protocol and summary answers during their tasks.

5.3.1 Trackpad Interaction is More Efficient and Less Tiring

During T1, some users reported that the smartphone was shaky and they have to stabilize the phone with both hands which adds to the physical demand. The task completion time (avg = 28.5 secs, std = 8.6 sec for trackpad mode vs. avg = 61.8 sec, std = 18.8 sec for

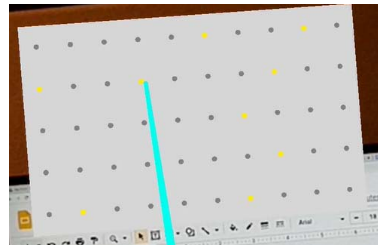

Figure 4: In raycaster mode, the participant selects a ball by pointing the ray at the ball and tapping on the smartphone touchscreen

raycaster mode) also reveals that trackpad mode is more efficient in the “Click” selection task. Some users also mentioned that even though they like the trakpad mechanism more than raycaster for selection, they expect a more suitable cursor moving rate, and one experienced difficulty seeing the cursor in the first place. We reckon these issues as UI design concerns are not central to our study but they might be worth exploring in future work.

5.3.2 Window Switch Mechanism Need Better Design

In T2 and T3, we expected users to take advantage of the multi-window interface so as to efficiently compare many subsets (e.g., crimes in different regions) at once. Efficient data comparison helps faster sensemaking. However, we observed the opposite – a significant portion of participants (16 out of 22) finished T2 and T3 using merely one window. Some of them reported the window switch mechanism as being bothersome and un-intuitive, which confused them and discouraged its use. Even though users were seemingly hesitant when it comes to window switches, some reported they were likely to window switch more had the mechanism itself become more fluent and easier to use.

5.3.3 Well Designed Window Management System is Needed

During T2 and T3, some participants get confused with the current window management system in the application. When we designed the system we separated window manipulation activities from interface manipulation activities and we designated raycaster mode and trackpad mode for either respectively. However, participants have shown a pattern of jumping between window manipulation and interface manipulation frequently. Some have experienced inconvenience due to the need for frequent mode changes – “Why is it designed this way? It’s very confusing” (P8). Since the usability of SPARVIS framework is tightly connected with a fluent window management system, like those on a modern desktop, we also think it is worth exploring in the future.

6 Discussion and Conclusion

SPARVIS is an ongoing project, and this paper primarily focuses on highlighting a set of four primary interactions that were essential to such a cross-device VDA experience. While we plan to conduct extensive evaluations with a wider user base and on more interactions, a formative study on two alternative implementations of the “Click” interaction has provided useful feedback and pointers about the design of such interactions. During our user study, users also expressed a need for a better window management technique for a more fluent workflow on the AR+smartphone duo. This might be a topic with great research value as it is fundamental to UI/UX design on AR+smartphone cross-device experience.

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